

# Optical and Near-Infrared Photometry of Nova V2362 Cyg : Rebrightening Event and Dust Formation

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## Abstract

We present optical and near-infrared (NIR) photometry of a classical nova, V2362 Cyg (= Nova Cygni 2006). V2362 Cyg experienced a peculiar rebrightening with a long duration from 100 to 240 d after the maximum of the nova. Our multicolor observation indicates an emergence of a pseudophotosphere with an effective temperature of  $\sim 9000$  K at the rebrightening maximum. After the rebrightening maximum, the object showed a slow fading homogeneously in all of the used bands for one week. This implies that the fading just after the rebrightening maximum ( $\lesssim 1$  week) was caused by a slowly shrinking pseudophotosphere. Then, the NIR flux drastically increased, while the optical flux steeply declined. The optical and NIR flux was consistent with blackbody radiation with a temperature of  $\sim 1500$  K during this NIR rising phase. These facts are likely to be explained by dust formation in the nova ejecta. Assuming an optically thin case, we estimate the dust mass of  $10^{-8} - 10^{-10} M_{\odot}$ , which is less than those in typical dust-forming novae. These results support the scenario that a second, long-lasting outflow, which caused the rebrightening, interacted with a fraction of the initial outflow and formed dust grains.

**Key words:** infrared: stars — ISM: dust, extinction — stars: novae, cataclysmic variables — stars: individual(V2362 Cyg)

## 1. Introduction

Classical novae are cataclysmic variable stars which are semidetached binary systems containing a late-type star and a white dwarf (WD). The nova outburst is induced by a thermonuclear runaway in the matter transferred from the late-type star onto the surface of the WD. A large amount of gas accumulated on the WD is ejected due to nova outbursts. The ejected mass is typically  $\sim 10^{-4} M_{\odot}$  in an outburst. The expansion velocity of the ejecta reaches  $\sim 10^2 - 10^3 \text{ km s}^{-1}$ . The outburst amplitude of novae is 10–15 mag in optical (Bode & Evans 1989).

Dust formation episodes are occasionally observed during nova outburst phases. The dust formation occurs 30

– 80 d after the maximum of the light curve. This phase is the “transition phase” (Bode & Evans 1989). We can study the formation and cooling processes of dust through the temporal evolution of novae.

V2362 Cyg (= Nova Cygni 2006) was discovered on April 2.807 UT by H. Nishimura at 10.5 mag (Nakano et al. 2006). Yamaoka et al. (2006) spectroscopically confirmed that it was a classical nova just around its maximum from the H $\alpha$  emission line with a clear P-Cygni profile. Siviero et al. (2006) reported that the nova belongs to the Fe II class. Steeghs et al. (2006) identified the progenitor of V2362 Cyg on their galactic plane survey images taken on 2004 Aug 3 as a point source with the magnitudes of  $r' = 20.3 \pm 0.05$  and  $i' = 19.76 \pm 0.07$ , which indicates the outburst amplitude of  $\sim 12$  mag.

The nova experienced an unusual rebrightening event from  $\sim 100$  d after the first maximum. The nova reached its rebrightening maximum on 2006 December 1.9 (= JD 2454071.4; Munari et al. 2008). A similar rebrighten-

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ing event has been found only in V1493 Aql (Bonifacio, Selvelli & Caffau 2000; Venturini et al. 1993). V2362 Cyg is the second case which exhibited such a rebrightening, and hence, has received much attention (Goranskij et al. 2006; Munari et al. 2006a; Lynch et al. 2006; Rayner et al. 2006; Kimeswenger et al. 2008; Lynch et al. 2008; Munari et al. 2008; Poggiani 2009). Most recently, V2491 Cyg showed a small rebrightening event and some authors suggested that V2491 Cyg belongs to the same class (Naik, Banerjee & Ashok 2009; Hachisu & Kato 2009; Takei et al. 2009). Such rebrightening events are totally unexpected from the standard picture of classical novae, and their mechanism is still unclear. Optical–near-infrared multi-band monitoring would be crucial to explore the temporal evolution of the photosphere and outflow material around the rebrightening event.

We performed extensive optical and near-infrared (NIR) photometric observations of V2362 Cyg covering the early decline and the rebrightening event of the object. Our data trace the evolution of outflow materials around the rebrightening event. In section 2, we describe our observations. The results are presented in section 3. We discuss the characteristics of the dust formation in section 4. Finally, we summarize our findings in section 5.

## 2. Observations and Data Reduction

We performed simultaneous optical and NIR observations during the rebrightening event with TRISPEC attached to the KANATA 1.5-m telescope at Higashi-Hiroshima Observatory. TRISPEC is an imager and spectrograph with a capability of polarimetry covering both optical and NIR wavelengths (Watanabe et al. 2005). The TRISPEC observation was conducted from 2006 November 20.56 UT (JD 2454060.06), 11 d before the rebrightening maximum, to 2007 February 5.87 (JD 2454137.37), 68 d after past the rebrightening maximum. We obtained typically 10 frames in a night with different dithering positions in individual bands. Exposure times in the  $B$ ,  $V$ ,  $R_c$ ,  $I_c$ ,  $J$ ,  $H$  and  $K_s$  in a night were typically 450, 380, 150, 155, 140, 180 and 75 s, respectively. We have no  $J$ - and  $H$ -band images between 2006 December 15 and 2007 January 18 because of a hardware problem.

We obtained differential magnitudes of the object relative to a comparison star using aperture photometry with the APPHOT package in IRAF<sup>1</sup>. We used a nearby star TYC 3181-1159-1 as a comparison star. Its magnitudes of  $B = 11.15 \pm 0.01$  and  $V = 9.70 \pm 0.01$  are quoted from Frigo et al. (2006) and  $J = 7.18 \pm 0.02$ ,  $H = 6.50 \pm 0.02$  and  $K_s = 6.35 \pm 0.02$  are from the 2MASS catalog (Skrutskie et al. 2006). We estimated the magnitude of the comparison star at  $R_c = 8.95 \pm 0.02$  and  $I_c = 8.26 \pm 0.03$ , using the other nearby stars listed in Frigo et al. (2006).

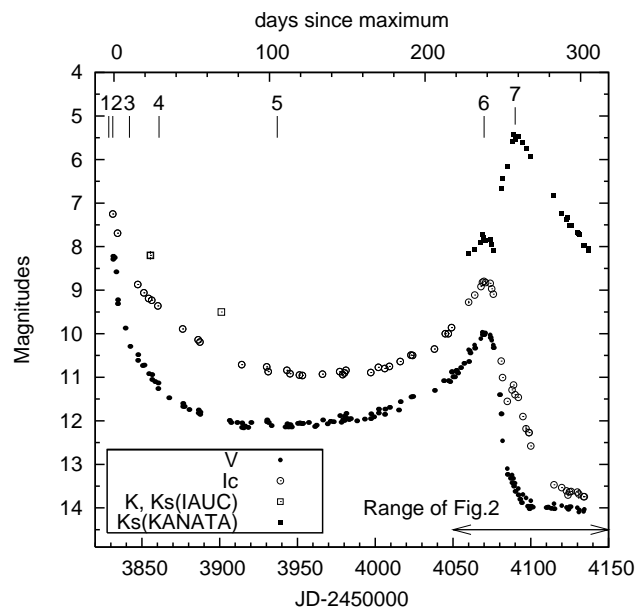
In addition to the TRISPEC/KANATA observation, we

performed optical CCD photometry of V2362 Cyg from 2006 April 5.8 (JD 2453831.3), around the first maximum, to 2007 January 23.4 (JD 2454123.9) with several telescopes in 30-cm class. For differential photometry, we used the nearby stars, TYC 3181-1511-1 and TYC 3181-1401-1 taken in the same frames including the nova.

For the correction of interstellar extinction, we used  $E_{B-V} = 0.58 \pm 0.02$ , which is an average of the values reported in Siviero et al. (2006), Russell et al. (2006) and Mazuk et al. (2006). We calculated the interstellar extinction in each band using the reddening curve presented in Rieke & Lebofsky (1985) and Schlegel et al. (1998).

## 3. Results

Figure 1 and 2 show the light curves of V2362 Cyg. The latter exhibits the light curves after the rebrightening maximum in detail.



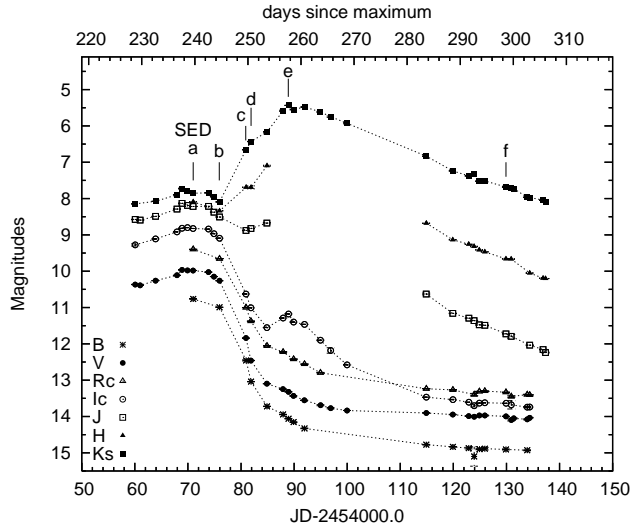
**Fig. 1.** Optical and NIR light curves of V2362 Cyg from 2006 April to 2007 February. The NIR data on 2006 April 30 (JD 2453855.5) and 2006 June 14.6 (JD 2453901.1) are quoted from Russell et al. (2006) and Mazuk et al. (2006), respectively. The lower horizontal axis indicates the time in JD. In the upper axis, we show the days from the first maximum, 2006 Apr 5.8 UT (JD 2453831.3). The vertical ticks indicate notable epochs shown in Table 1.

### 3.1. The First Maximum and Early Decline

The nova reached its first maximum at  $V=8.2$  on 2006 April 5.8 in our data. In this paper, we denote the fiducial time by  $t$ , in days, where  $t=0$  is defined at the first maximum. We estimated  $t_2 = 10.5 \pm 0.5$  and  $t_3 = 29 \pm 1$  from our  $V$ -band light curve, where  $t_2$  and  $t_3$  are the time taken for the nova to fade by 2 and 3 mag from the maximum, respectively.

Our  $t_3$  is slightly longer than those in other studies (Kimeswenger et al. 2008; Munari et al. 2008; Poggiani

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**Fig. 2.** Light curves before and after the rebrightening maximum. The six vertical lines indicate epochs of spectral energy distribution (SED) shown in figure 3.

2009). This is because our maximum magnitude  $V = 8.2$  is fainter than others ( $V = 7.8\text{--}8.0$ ) due to the sparseness of our observation around the maximum. Even in  $t_3$  estimated with our data, V2362 Cyg is included in the fast nova, as reported in the other studies.

In the early decline phase ( $t = 0\text{--}100$ ), the nova showed a monotonous decline without a transition phase, as can be seen in figure 1. This figure also shows the NIR observations reported in Russell et al. (2006) and Mazuk et al. (2006). We estimated the reddening-corrected color  $V - K_s = 1.2 \pm 0.1$  and  $V - K = 0.8 \pm 0.1$  on  $t = 24$  and  $t = 70$ , respectively. The characteristics of the light curve and color were well consistent with those of typical fast novae.

### 3.2. Rebrightening and Subsequent Decline

The unusual rebrightening started on  $t \sim 100$ , as can be seen in figure 1. The slope of the light curve gradually increased until  $t = 240$  when the object reached the apparent maximum at  $V = 10.0$ .

Our multi-band photometric observations allow us to

**Table 1.** Characteristic epochs of V2362 Cyg.

Epoch	Remark	$t$ days	$V$ -mag
1	Discovery	$-3.0^*$	$10.5^*$
2	First maximum	0	8.2
3	$t_2^{**}$	$10.5 \pm 0.5$	
4	$t_3^{**}$	$29 \pm 1$	
5	Onset of rebrightening	$\sim 100$	12.1
6	Rebrightening maximum	$240^\dagger$	10.0
7	$K_s$ maximum	258	13.3

\* Using photographic films (Nakano et al. 2006). \*\*  $t_n$  is at the date which the nova faded by  $n$  magnitudes from the maximum in  $V$ -band.  $^\dagger$  The date of the rebrightening maximum is JD 2454071.4.

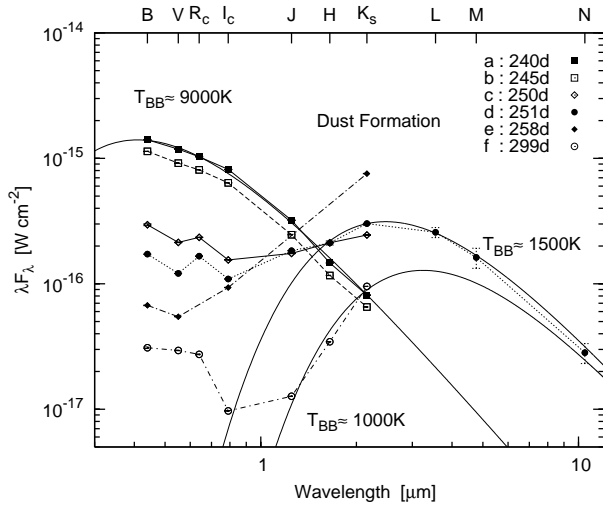
study the spectral energy distribution (SED) of the optical–NIR regime during the rebrightening. Figure 3 shows the observed SEDs. In this figure, we draw 6 SEDs at epoch (a, b, c, d, e, and f) which are shown in figure 3 and also indicated in figure 2. At epoch a, the observed SED can be described with a blackbody emission as shown in figure 3. We derived the best-fit temperature at  $T = 9000 \pm 200$  K. The SED, hence, indicates that the optical–NIR flux was dominated by an optically thick pseudophotosphere at the rebrightening maximum.

In ordinary novae, the blackbody-like photospheric emission dominates the optical flux only around the maximum light. In the case of V2362 Cyg, Czar et al. (2006) reported the optical spectrum during the earliest phase, and suggested that its blue spectrum resembled that of an A5–A7 supergiant. This indicates that the optical emission was dominated by a pseudophotosphere with  $T = 8000\text{--}8600$  K at the outburst maximum (Cox 2000). The photospheric temperature at the rebrightening maximum was, therefore, comparable to or slightly higher than, that at the first maximum, while the rebrightening maximum was fainter. Assuming blackbody emission, we can readily compare the sizes of the emitting region at the initial and rebrightening maxima using the apparent  $V$ -magnitude and the temperatures. As a result, the diameter of the photosphere at the rebrightening maximum is estimated to be about half of that at the first maximum.

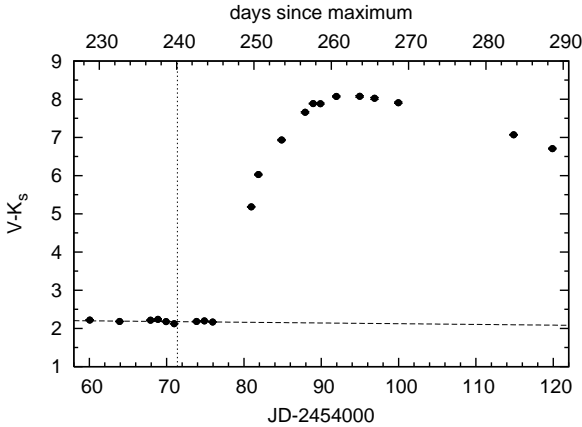
After the rebrightening maximum, the object started a gradual fading in all optical–NIR bands. The  $V - K_s$  color just before and after the rebrightening maximum is shown in figure 4. There was no significant change across the rebrightening maximum, i.e., in  $t = 228\text{--}245$ . This suggests that the shape of the SED remained almost constant irrespective of the flux variation across the rebrightening maximum ( $\Delta V \sim 0.5$ ).

Sudden brightenings in  $H$ - and  $K_s$ -bands were then detected on  $t = 250$  (epoch c). As shown in figure 3, the pseudophotosphere component rapidly decreased, while another NIR component increased around the epoch. The brightening was observed in  $J$ - and  $I_c$ -bands a few days later. In figure 3, we plot  $L$ -,  $M$ -, and  $N$ -band data on  $t = 251$  (epoch d) reported by Lynch et al. (2006) and also give blackbody spectra with temperatures of 1500 and 1000 K. The 1500 K blackbody spectrum well explains the observed IR SED on  $t = 251$ . Hence, this IR emission can be interpreted as the thermal emission from dust grains. Munari et al. (2008) and Lynch et al. (2008) reported the dust temperature of 1550 K on  $t = 251$  and 1410 K on  $t = 260$ , respectively. The dust shell would be formed, presumably associated with the rebrightening event. The rapid decrease of the pseudophotosphere component is likely to be connected with the increasing absorption by the dust shell.

After the  $K_s$ -band maximum on  $t = 258$  (epoch e), the object faded in all optical–NIR bands. At  $t = 299$  (epoch f), as shown in figure 3, the NIR emission can be described with the 1000 K blackbody spectrum. Lynch et al. (2007) reported the dust temperature was below  $< 520$  K on  $t \sim 422$ . The dust cooling, thus, seems to have started just



**Fig. 3.** Optical and NIR SED of V2362 Cyg at six epochs. The solid lines indicate single-temperature blackbody radiations (9000 K, 1500 K and 1000 K). The  $L$ -,  $M$ - and  $N$ -band data on  $t = 251$  (epoch d) were quoted from Lynch et al. (2006). Epoch ‘a’ is almost at the rebrightening maximum and ‘e’ is at the  $K_s$ -band maximum. The interstellar extinction was corrected as described in § 2.



**Fig. 4.**  $V - K_s$  color before and after the rebrightening maximum. The interstellar reddening is not corrected for. The vertical dotted line indicates epochs of the rebrightening maximum. The horizontal dashed line indicates the best-fitted line of  $V - K_s$  between  $t = 229$  and  $t = 245$ .

after the  $K_s$ -band maximum, probably due to cessation of the dust formation and expansion of the dust shell.

## 4. Discussion

### 4.1. Estimation of the Dust Mass

Assuming an optically thin dust cloud and a distance to V2362 Cyg of  $d = 7.2$  kpc, Munari et al. (2008) estimated the mass of carbonaceous dust grains of  $M \sim 10^{-9} M_\odot$ . However, they underestimated the dust mass because they used the NIR flux at pre-maximum phase (epoch d; 7 days before the  $K_s$  maximum) when the bolometric luminosity

of the dust cloud ( $L_{\text{dust}}$ ) was still 0.4 times as large as the maximum value on epoch e. The uncertainty of the distance should also be considered for the error estimation of the dust mass. Then, we estimate the dust mass of V2362 Cyg with our data under the same assumption as Munari et al. (2008) that carbon dusts were formed after the rebrightening. Although the late time observation ( $t = 443$ ) suggests that the IR spectrum was not typical for carbonaceous dust emission (Lynch et al. 2008), the dominant species could be changed with epochs (e.g., QV Vul, Gehrz et al. 1992; V705 Cas, Mason et al. 1998).

According to Woodward et al. (1993), the mass of the dust cloud ( $M_{\text{dust}}$ ) is derived as

$$M_{\text{dust}} = \frac{4\pi}{3} N \rho a^3 \approx 1.1 \times 10^6 \left( \frac{d}{1 \text{ kpc}} \right)^2 \left[ \frac{(\lambda F_\lambda)_{\text{max}}}{1 \text{ W cm}^{-2}} \right] \left( \frac{T_{\text{dust}}}{1000 \text{ K}} \right)^{-6} M_\odot, (1)$$

where  $d$  is the distance to the nova,  $N$  is a number of total dust grains and  $T_{\text{dust}}$  is a temperature of dust grains. We assume graphite dust grains of a density of  $\rho = 2.25$  and a Planck-mean cross section coefficient  $Q \sim 10^{-2} a T^2$  (for smaller grains with size of  $a \lesssim 0.5 \mu\text{m}$ ; Gilman 1974; Woodward et al. 1993). Adopting  $T_{\text{dust}} = 1500$  K estimated from the IR data in  $t = 251$  (epoch d) and  $(\lambda F_\lambda)_{\text{max}} = 7.6 \times 10^{-16} \text{ W cm}^{-2}$  in our data at NIR maximum ( $t = 258$ , epoch e), we obtain

$$M_{\text{dust}} \sim 7.3 \times 10^{-11} \left( \frac{d}{1 \text{ kpc}} \right)^2 M_\odot. (2)$$

We note that the deriving mass does not mean the whole mass formed in the ejecta after the rebrightening event, but the mass evaluated at the NIR maximum ( $t = 258$ , epoch e).

$M_{\text{dust}}$  highly depends on the distance  $d$ , although it has not been determined well;  $d = 1.5$  kpc (Czart et al. 2006), 5–12 kpc (Steehgs et al. 2006), 5.5–10.0 kpc (Kimeswenger et al. 2008),  $7.2 \pm 0.2$  kpc (Munari et al. 2008) and 7.2–15.8 kpc (Poggiani 2009). For the nearest ( $d = 1.5$  kpc) and the most distant ( $d = 15.8$  kpc) cases, the  $M_{\text{dust}}$  becomes  $\sim 2 \times 10^{-10} M_\odot$  and  $2 \times 10^{-8} M_\odot$ , respectively. Even if we take the uppermost value,  $M_{\text{dust}}$  is comparable to or smaller than those of ordinary dust-forming novae ( $10^{-6}$ – $10^{-8} M_\odot$ ; e.g. Gehrz et al. 1998).

It is noted that the dust mass should be larger if the dust cloud is optically thick as indicated by Lynch et al. (2008). If this is the case, the derived  $M_{\text{dust}}$  should be the lower-limit and the actual dust mass would be larger. On the other hand, our NIR data suggests that  $L_{\text{dust}}$  is only 0.4–0.5 times as large as the bolometric luminosity of nova ( $L_{\text{nova}}$ ) even at the  $K_s$  maximum, if we assume  $L_{\text{nova}} = 1.3 \times 10^{38} \text{ erg s}^{-1}$  with  $d = 7.2$  kpc as Munari et al. (2008).  $L_{\text{dust}}$  is calculated by integrations of blackbody SEDs fitted with  $K_s$ -band data assuming dust temperatures with a range of  $T = 1410$ – $1500$  K and  $d = 7.2$  kpc. These facts suggest that the dust cloud does not fully cover the nova (i.e., covers by less than  $4\pi$  str), if the dust cloud was optically thick. A patchy cloud is preferable.



#### 4.2. Rebrightening and Dust Formation in the Second Mass-Flow

Munari et al. (2006b) and Kimeswenger et al. (2008) detected P-Cygni profiles in the optical spectrum of V2362 Cyg during its rising phase to the rebrightening maximum ( $t \sim 170$ ). In conjunction with the existence of the blackbody emission of  $T \sim 9000$  K, the rebrightening phase is reminiscent of the maximum phase of ordinary novae (Bode & Evans 1989). We propose that the rebrightening event was caused by the reformed pseudophotosphere by a delayed mass-outflow. Hachisu & Kato (2009) recently proposed that the energy source of the rebrightening is magnetic reconnections around the pseudophotosphere formed by the first outflow. Such a magnetic activity may have accelerated the gas and caused the second outflow in V2362 Cyg.

As discussed in section 4.1, the mass of the dust grains formed after the rebrightening is likely to be smaller than those in other dust-forming novae. If the dust grains are formed in the first ejecta cooled predominantly by expansion (i.e., classical dust formation mechanism, e.g., Clayton & Wickramasinghe 1976) the epoch of the dust formation is expected to be earlier ( $t \simeq 30 - 100$  d) and the dust mass should be larger, as in ordinary dust-forming novae.

The ejecta of the second outflow would contain less materials than that of the initial outflow because the peak luminosity of the rebrightening was much lower than the initial peak. Thus, masses are considered to be small for both the dust and the ejecta in the second outflow. This suggests that the dust grains would be formed preferentially from the material of the second outflow, if the Lynch et al. (2008)'s scenario that the dust formation would be triggered by the interaction between the second outflow and the initial flow is the case.

#### 4.3. The Termination of the Rebrightening

Here we briefly discuss the nature of the termination of the rebrightening, i.e., the beginning of the decline on  $t \sim 240$ . We can consider two scenarios; (i) the rebrightening was terminated due to the increasing absorption for the optical-NIR flux by the dust grains, and (ii) the rebrightening was terminated by a decay of the emission from the pseudophotosphere itself. If the former scenario is true, we could expect the reddening of the object just after the rebrightening maximum. As shown in figure 4, however, no reddening was detected for the first 4 d just after the rebrightening maximum. The observation, hence, favors the latter scenario. If scenario (ii) is the case, the dust grains are likely to begin to be formed about a week after the rebrightening maximum. This implies that the dust formation might be promoted by the decay of the emission from the shrinking pseudophotosphere. The optical steep decline with the NIR brightening after  $t \sim 250$  suggests that the increasing absorption due to dust formation is significant. However, the shrinking pseudophotosphere might also have partly caused the decline of the optical flux (and a part of NIR one). A full analysis with

a radiation transfer for the pseudophotosphere and the dusty ejecta would be required to reproduce the observed light curves, which is out of the scope of this paper.

### 5. Summary

We carried out optical and NIR photometry of Nova V2362 Cyg for  $\sim 300$  days from the first maximum. Our observation indicates the re-appearance of pseudophotosphere with  $T \sim 9000$  K around the rebrightening maximum. The NIR flux began to increase a week after the rebrightening maximum, accompanied with the steep decline of the optical flux. The  $K_s$ -band flux peaked at  $t = 258$ . The NIR flux at the peak is well explained by the thermal dust emission with  $T_{dust} \sim 1500$  K. The dust temperature then decreased from 1500 K to  $\sim 1000$  K within 40 days. We estimate the dust mass of  $M_{dust} \sim 2 \times 10^{-10} - 2 \times 10^{-8} M_{\odot}$ . This supports that the dust would be formed preferentially from the material of the second outflow, if the dust formation would be triggered by the interaction between the second flow and initial one as suggested in Lynch et al. (2008).

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